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Technical Report

EVALUATION OF AN IMPROVED RFI-SUPPRESSING POWER CONDUCTOR

13 January 1964

U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

EVALUATION OF AN IMPROVED RFI-SUPPRESSING POWER CONDUCTOR

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by

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ABSTRACT

An improved power conductor for suppressing radio frequency interference (RFI) was developed, consisting of #2 AWG stranded copper wrapped with two layers of 7-mil Silicon Iron (SiFe) magnetic tape and a 50-mil extruded polyvinyl chloride jacket. To evaluate its capability for attenuating RFI and its resistance to deterioration, the lossy conductor was installed on a 3-mile, 3-conductor, 4-kv power line on San Nicolas Island, off the coast of Southern California.

Attenuation exceeded that reported for the Fort Huachuca lossy line, at frequencies below 1 mc, and was equal or greater at higher frequencies. The stranded conductor's effect on attenuation is discussed, and curves are included for comparing the attenuation of solid and stranded conductors wrapped with lossy tape. Ambient noise levels are shown.

The severe climate and its effect on the power line are discussed; test methods are described; and future developments are considered.

INTRODUCTION

This report describes the design, test, and evaluation of a new configuration of the interference-suppressing power conductor previously reported.* To measure its attenuation capabilities and resistance to deterioration, the new configuration was installed, replacing 3 miles of the old 3-phase 4-kv Corvus line, on the northwest tip of San Nicolas Island. This location, as part of the Naval Pacific Missile Range complex, is electromagnetically sensitive, and power line maintenance is a serious problem.

DEVELOPMENT OF THE IMPROVED RFI-SUPPRESSING POWER CONDUCTOR

The first configuration, evaluated at Fort Huachuca, consisted of a solid, cylindrical conductor, wrapped with metal tape (Figure 1). The conductor was wrapped with high-permeability metal tape to increase the conductor's so-called "skin effect." This term refers to the natural tendency for high-frequency currents to flow just on and beneath the surface or "skin" of the conductor. The skin effect is a function of frequency; the higher the frequency the greater the current density in the skin of the conductor. At very low frequencies such as the 60 cps of power lines, this skin effect may be considered negligible. The attenuation of 60-cycle power by the developed conductor is actually lowered by the tape which adds extra conductor and slightly increases characteristic impedance. The skin effect may be considered as a frequency-selective low-pass filter effect inherent in the wrapped conductor because the wrapped conductor attenuates higher frequencies more than lower frequencies.

Skin depth is defined as that depth from the conductor surface at which the current density is reduced to 1/2.718 of that flowing at the surface. It may also be expressed as $\delta = 1/\sqrt{\pi \mu \sigma f}$ where μ = permeability of the conductor, σ = conductivity of the conductor, f = frequency in cycles per second. For a copper conductor, $\delta = 6.64/\sqrt{f}$ cm. For example, at 60 cycles δ is 0.86 cm; whereas at 1 mc it is 0.0066 cm.

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* Technical Report R-178, Evaluation of the Interference-Suppressing Power Conductor, by D. B. Clark and J. L. Brooks. Port Hueneme, California, 20 December 1961.

A high-permeability material wrapped around a conductor causes a significant increase in the tendency of the current to crowd to the surface. The ac resistance of the conductor is greatly increased when the current flows in a smaller volume of the conductor. At high frequencies the expression for ac resistance of a conductor wrapped with high-permeability metal tape becomes simply:

$$R_{ac} = \frac{\sqrt{\pi f \mu_1}}{2\pi b \sqrt{\sigma_1}}$$

where R_{ac} = the high-frequency or ac resistance of the conductor

μ_1 = permeability of the wrapping

b = outside radius of wrapped conductor

σ_1 = conductivity of the wrapping

This equation indicates that the high-frequency current is flowing in the wrapping only.

The results of the tests on the new conductor show that the attenuation which is proportional to R_{ac} begins to approximate the $\sqrt{f}$ function of the above equation at about 100 kc. In the frequency range from 200 kc to 40 mc, this yields attenuation of from 10 to 100 db per mile for a 3-wire overhead transmission line with wrapped conductors, as compared to 2 to 5 db per mile for the line with bare #6 conductors.

The attenuation does not follow the $\sqrt{f}$ curve at the lower frequencies because not all of the current is drawn into the skin and wrapping at these frequencies, and the expression for ac resistance is a complex equation involving Bessel-type functions. There are two methods of increasing the ac resistance at the low frequencies: (1) to add more high-permeability tape (but this adds weight without adding materially to the power-carrying capacity, although larger-diameter conductors could support more layers of tape); or (2) to use smaller-diameter conductors (but this would limit both the voltage and power current rating). The preferred method is to alter the conductor surface configuration in such a manner that the current flowing near the surface is forced to flow through a smaller cross-sectional area. One common conductor configuration which gives this effect is the stranded conductor (Figure 2). Several laboratory tests were conducted on stranded conductors wrapped with high-permeability tape; the results are given in Figure 3.

In order to directly compare the results for wrapped stranded conductors to the results with the wrapped solid conductor used in the Fort Huachuca tests, the equivalent differences in diameter of the two conductors was accounted for and the comparison is shown in Figure 3. A multiplying factor may be calculated as follows:

$$\alpha = \frac{R_{ac}}{2Z_o} \text{ and } R_{ac} = \frac{1}{2\pi b} \frac{\sqrt{\omega\mu}}{\sqrt{2\sigma}}$$

where Z_o is the characteristic impedance and $\omega = 2\pi f$. Then, substituting for the radii of the two conductors used,

$$\frac{R_{ac}\,(\#6 \text{ AWG solid})}{R_{ac}\,(\#2 \text{ AWG solid})} = \frac{\dfrac{\sqrt{\omega\mu}}{2\pi\sqrt{2\sigma}}\left(\dfrac{1}{.081}\right)}{\dfrac{\sqrt{\omega\mu}}{2\pi\sqrt{2\sigma}}\left(\dfrac{1}{.132}\right)} = 1.63$$

The comparison in Figure 3 is made between #2 AWG stranded copper, and the equivalent #2 AWG solid copper conductor. The latter has the same total copper cross-sectional area as the #2 AWG 7-strand conductor used at San Nicolas, thus the same 60-cycle power current capacity.

A 100-foot sample of the #2 AWG stranded conductor wrapped with double SiFe mag tape was checked for saturation characteristics. The results of this test are shown in Figure 4 for 1 mc.

Previous tests of available magnetic tapes have shown the SiFe mag tape to be the best considering permeability and power current saturation effects. On the basis of these and other laboratory tests a contract was let to a manufacturer to fabricate 9 miles of #2 AWG stranded copper conductor wrapped with a double layer of SiFe mag tape, 7 mils thick, 1/2 inch wide, and coated with an extruded 50-mil layer of polyvinyl chloride for protection from corrosion. This wire was shipped to the Laboratory on 7 September 1962.

EVALUATION OF THE IMPROVED RFI-SUPPRESSING POWER CONDUCTOR

Test Site

San Nicolas Island was chosen as the test site for several reasons. First, it is a part of the Naval Pacific Missile Range complex and has a definite requirement for RFI suppression. Second, the island is about 50 miles from the mainland and is subjected to extreme weather conditions which cause corrosion, rusting, and rapid deterioration of facilities. Third, a section of power line there has a history of failures caused by leakage due to sand and salt encrustation, and the line is not critical to the continuous operation of the range facilities. Fourth, the island is near NCEL, where it can be monitored at nominal cost.

The Public Works Department of NPMR provided the necessary assistance in administering the installation contract and gave assistance in supporting the field tests.

Ambient Noise on Test Site

To obtain information concerning the ambient noise levels in the area around the Corvus power line on San Nicolas Island, measurements were made there with the line normally energized from 31 July to 2 August 1962, before the new line was installed. EMI meters were set up directly underneath the line and the noise levels between 10 kc and 1000 mc were recorded (Figure 5). This was done at numerous locations in the vicinity of the line. Ambient noise was also recorded at a remote beach location away from any lines (Figure 6). Figure 7 shows the radiated ambient noise level 100 feet beyond a 1750-foot spur or feeder from the main line before and after both were replaced with the lossy conductor.

Field Tests

The installation was completed in November 1962 and arrangements were made to run an evaluation test from 10-13 December 1962.

<u>Tests With Impulse Noise Gap Generators</u>. To determine noise attenuation along the transmission line, a signal was injected into the line at one end and the propagated noise was measured at different distances from the source. The noise sources used were of the impulse noise gap type employed in the 13-kv tests at Fort Huachuca. Figure 8 shows the noise generators in operation. The metal plates provided additional capacitance to the noise gap generators, for greater output at the lower 4-kv voltage at San Nicolas Island.

Field intensity tests were made at distances of 40, 285, 410, 580, 815, 910, and 1410 feet, measured from directly beneath the noise generators. The EMI meters used covered the range from 15 kc to 1000 mc; they are listed in Table I. Power for the instruments was provided by two AN/GSA-14 suppressed 60-cycle generators, which were carried in one of the vehicles (Figure 9).

Table I. EMI Meters Used

EMI Meter	Serial No.	Frequency Range
NM10A	159-7	15 kc to 250 kc
NM20B	140-6	150 kc to 25 mc
NM30A	208-36	20 mc to 400 mc
NM52A	292-41	375 mc to 1000 mc

Because of the lower voltage (4 kv rms) and higher attenuation of the line, the initial noise signal intensities were not as large nor could they be measured as far down the line as at the Fort Huachuca line (which was 13 kv rms). Figure 10 shows one of the tests in progress.

Tests With the Impulse Noise Power Generator. The noise signals generated on the line by the impulse gap generators were so rapidly attenuated that a different approach was tried on the last 1-mile section of the line. A newly developed noise generator designed to deliver very large amounts of impulse noise* was connected to the far end of the transmission line at the point where it entered a step-down transformer. The last 1 mile of the line was deactivated by opening existing air disconnects, and the noise generator was coupled directly onto the high-voltage side of the transformer with all three phases tied together. To insure a constant level during the testing period, a current probe and EMI meter monitored the noise induced on the line (Figure 11).

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* NCEL Technical Note N-474, Large Power Impulse Noise Generator for Evaluation of RFI Shielding and Filtering, by D. B. Clark. Port Hueneme, California, 19 November 1962.

The 3-phase conductor connecting the transformer to the overhead 4-kv line travels first through 700 feet of underground conduit. The first set of measurements were taken under the first span of overhead line and the rest at successive intervals from this end. A considerably higher noise level was available with the new noise generator, and it was possible to measure further down the 1-mile line before running out of noise signals. The readings were taken at distances of 0.01, 0.14, 0.24, 0.49, and 0.94 mile from the point where the line went underground. Because the terrain was rough and inaccessible in places, locations for measurements were limited to spots with accessibility directly under the line.

The data from this set of measurements was analyzed by a computer fit to the equations for waves propagated and reflected from a mile of transmission line, as described in the Appendix. The attenuation values obtained from both this test and the test at the beginning of the line were combined, and the results are shown graphically in Figure 12.

DISCUSSION

Attenuation

As shown in Figure 12, the results of the evaluation test on the San Nicolas Island installation indicate a higher attenuation than at Fort Huachuca (Figure 13). The low-frequency end of the attenuation curve of the San Nicolas line (below 1 mc) remains considerably higher than that of the Fort Huachuca line. This result was predicted by the laboratory test results shown in Figure 3. It can be expected since it occurs in the frequency region when the current is still flowing partially in the copper, and the outer skin of the stranded conductor provides a much smaller cross section than does the solid cylinder. At much higher frequencies the majority of the current is in the tape, and the copper surface configuration has little effect. Figures 5 and 7 show that after the lossy conductor was installed, the noise under and around the power line was considerably less for frequencies below 7 mc (Figure 5) and below 100 mc (Figure 7). Above these frequencies the measured noise was essentially that of the measured free ambient (Figure 6).

Resistance to Deterioration

As stated, San Nicolas Island is subjected to extreme weather conditions. The aerial power lines on the island are continually subjected to salt spray and sand; this results in much current leakage. The particular line chosen has a poor historical record because of a sandy environment and proximity to the shore. These conditions provided an ideal weather testing environment for the newly developed

lossy line. The SiFe mag tape wrapping, unless properly protected, is subject to more rapid deterioration than an ordinary copper conductor. Figure 14 shows the sand encrustations and weathering on the pole insulators and line connections on the new lossy line two months after it was installed at San Nicolas and emphasizes the severity of the climate. To evaluate the effects of corrosion and weathering on San Nicolas Island, several 6-foot samples of line were tacked up on one of the poles to be taken down periodically for examination (Figure 15).

One 6-foot sample of the line was examined after being exposed, for about one year, to the San Nicolas environment. The ends of the sample were not sealed, and moisture was able to penetrate into the stranded conductor from the ends. Noticeable corrosion deposits were present in the first two inches, with minor deterioration further in. Corrosion by-products were examined and were found to be from the SiFe wrapping exclusively. Corrosion was not excessive, and the corrosion rate decreases with time due to the protection to surfaces provided by the corrosion material. The polyvinyl chloride jacket was in excellent condition. During one year of operation the line has required no maintenance and given no troubles.

Cost

The special conductor was obtained through normal purchasing channels and manufactured in accordance with brief specifications. The lossy tape was purchased separately to be sure of its quality and supplied to the manufacturer of the special conductor. The cost of the special conductor was approximately $0. 15 per foot. This was within the range of prices quoted by some other manufacturers for basic hard-drawn #2 AWG stranded copper.

The cost of the SiFe mag tape was approximately $0.035 per foot of the special conductor. The total cost of $0. 185 per foot for the special lossy conductor wrapped with the SiFe tape was less than the installation costs for removing the existing line on the isolated island and replacing it with the special conductor. In short, the cost of an initial installation, using this particular special conductor, would be very little different from that of a normal installation.

CONCLUSIONS AND RECOMMENDATIONS

The results of these tests indicate that greater attenuation of noise ambients is obtained from the stranded-conductor power line wrapped with SiFe mag tape than from solid conductor wrapped with the same tape. In this particular installation with #2 AWG stranded conductor, the second layer of SiFe mag tape was used to counteract the loss of attenuation due to increase in conductor diameter. For larger conductors more layers of tape would be advantageous.

If conductor ends were sealed to protect against moisture intrusion, it is expected that corrosion and deterioration of the SiFe tape wrapping would not be a factor of concern in the proper operation of the interference attenuating line. Mechanically, the line will not be affected by this corrosion, since only the copper is relied upon for mechanical strength.

This lossy line installation is an economical and effective RFI filter, being utilized in actual operating conditions. It is recommended that the last mile or so of power lines which feed electromagnetically sensitive military areas be of the lossy type. The required lossy conductor configuration depends on the voltage and current ratings necessary.

FUTURE DEVELOPMENT

Simulated lightning surge tests on 2600 feet of the #2 AWG lossy conductor described in this report, with surge voltages up to 820 kv, showed better attenuation of the surge crest voltages than did an untreated line. A report is being prepared on the surge and corona testing of this conductor.

Preliminary tests indicate that a copper conductor with a threaded surface wrapped with layers of SiFe mag tape can provide twice the attenuation of the solid conductor. This new configuration will be manufactured as both 15-kv shielded underground conductor and as 13-kv overhead transmission line. It will be installed for test at the Hawaiian Tracking Station, South Point, Kau, Hawaii.

Figure 1. #6 AWG solid copper conductor wrapped with 7-mil SiFe mag tape.

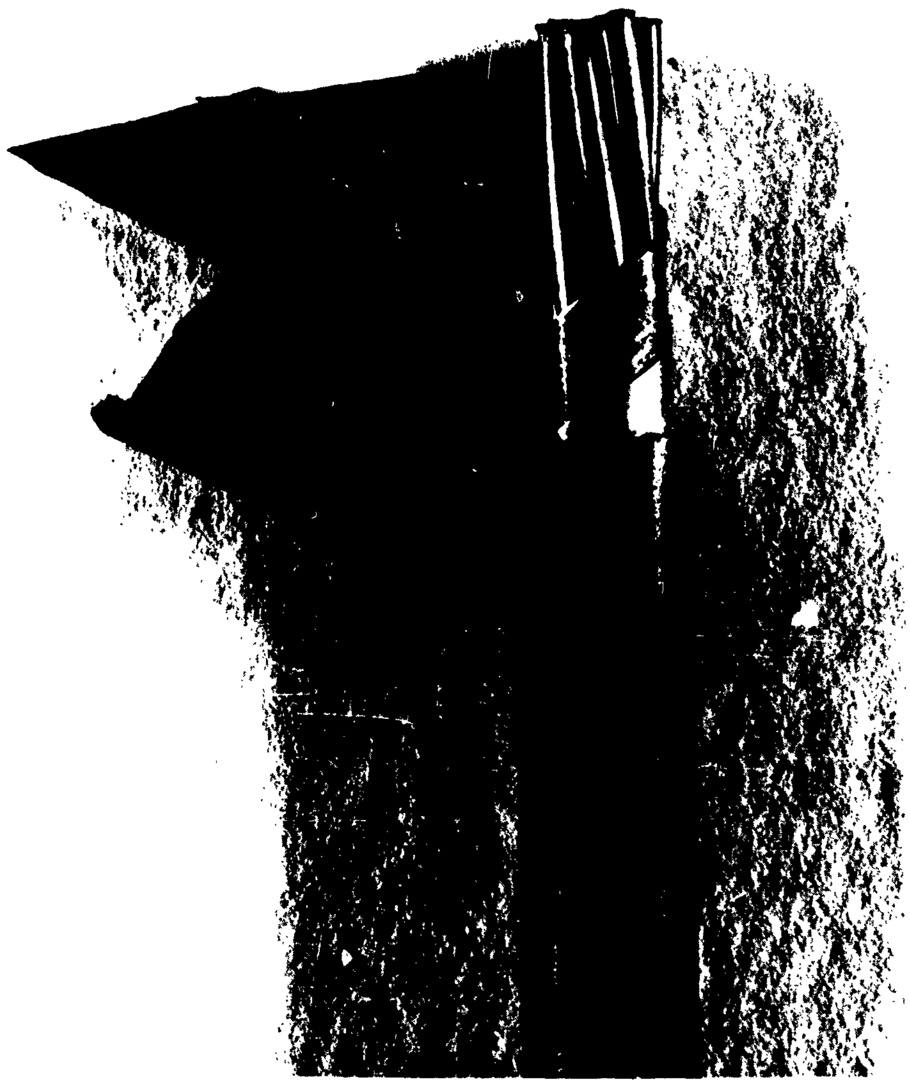

Figure 2. #2 AWG stranded copper conductor wrapped with 7-mil SiFe mag tape.

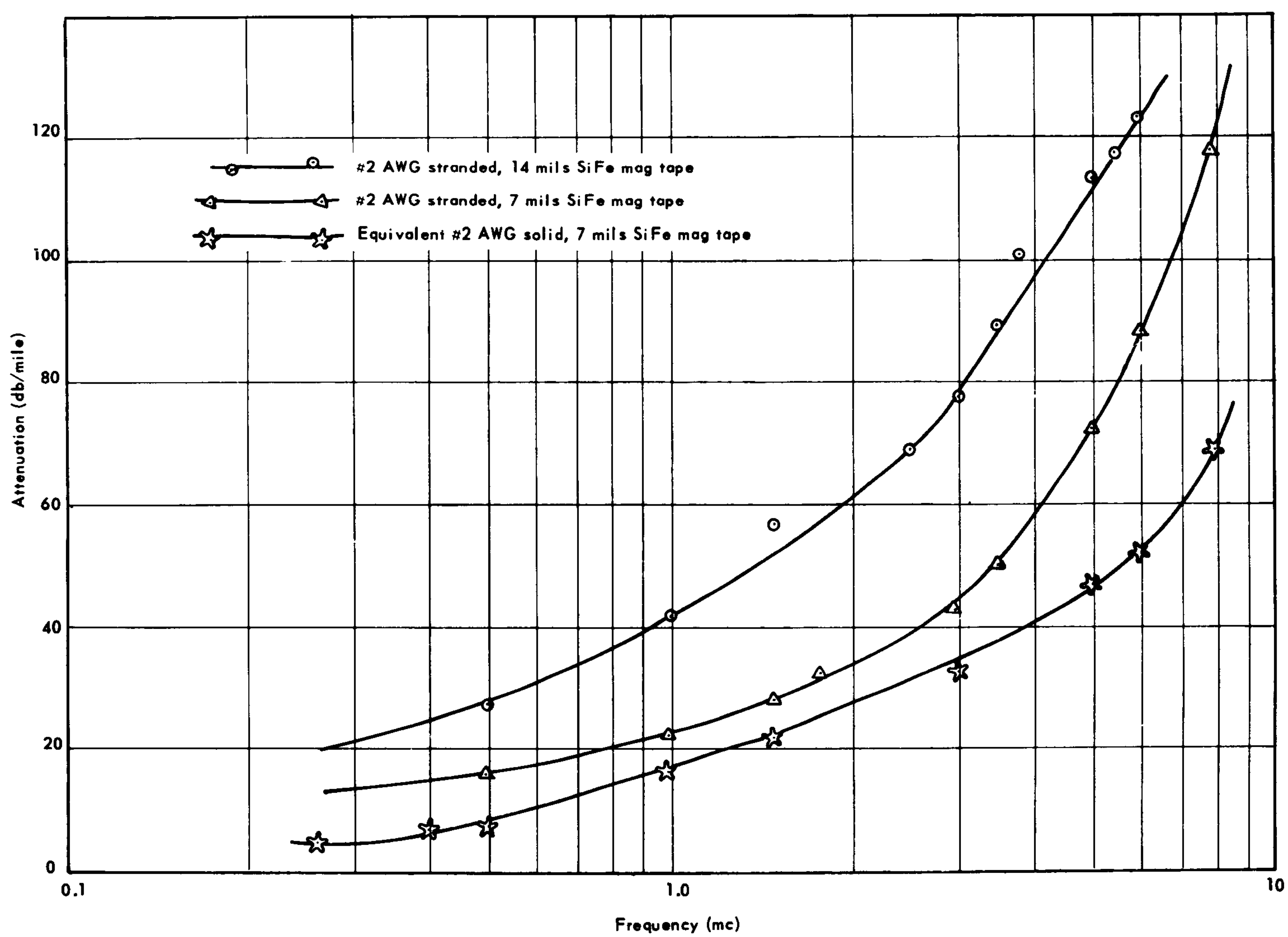

Figure 3. Comparison of attenuation by solid and stranded copper conductors wrapped with SiFe mag tape.

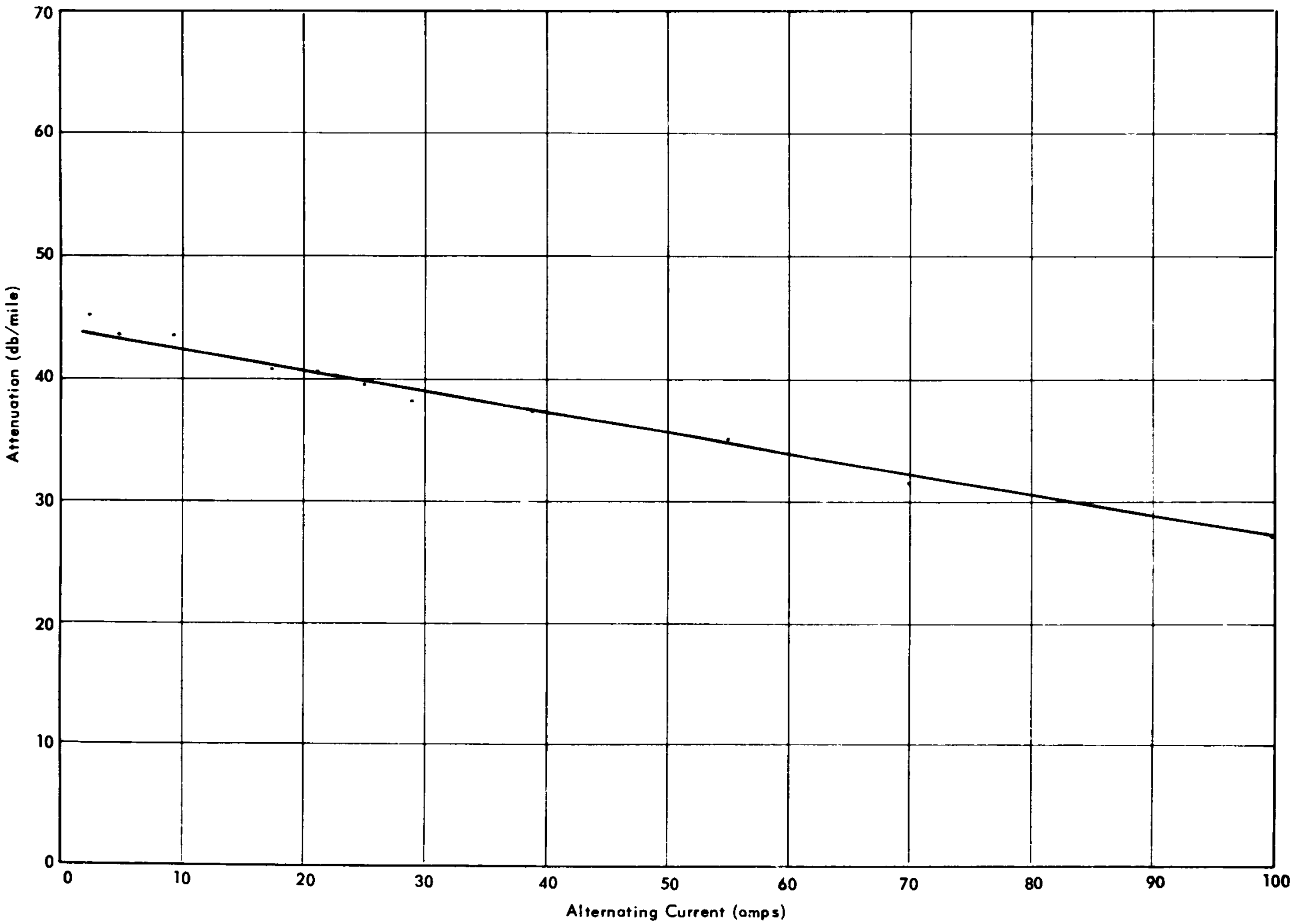

Figure 4. Saturation characteristics of #2 AWG stranded copper wrapped with 14 mils of SiFe mag tape.

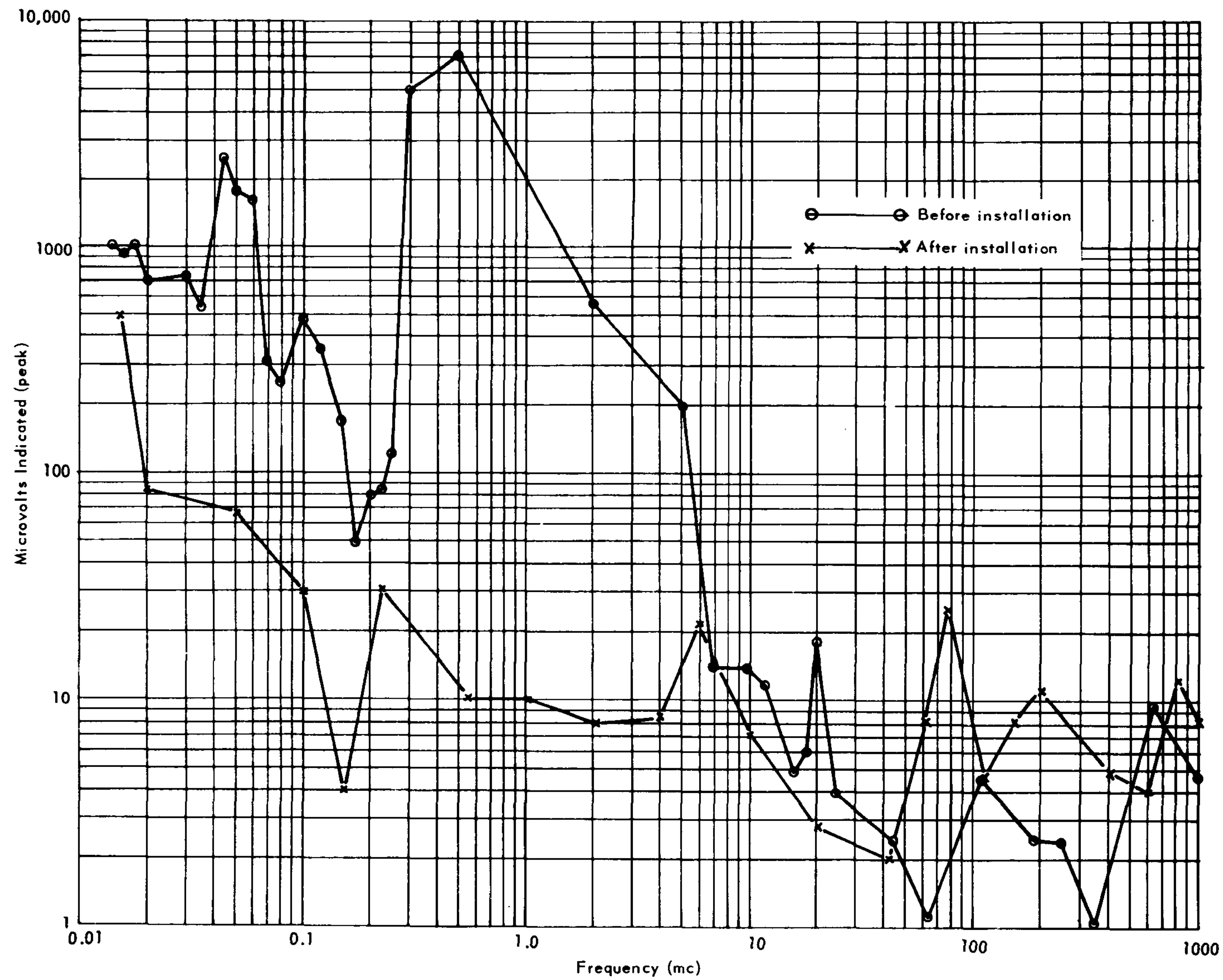

Figure 5. Noise under power line, 700 feet from beginning, before and after installing lossy line.

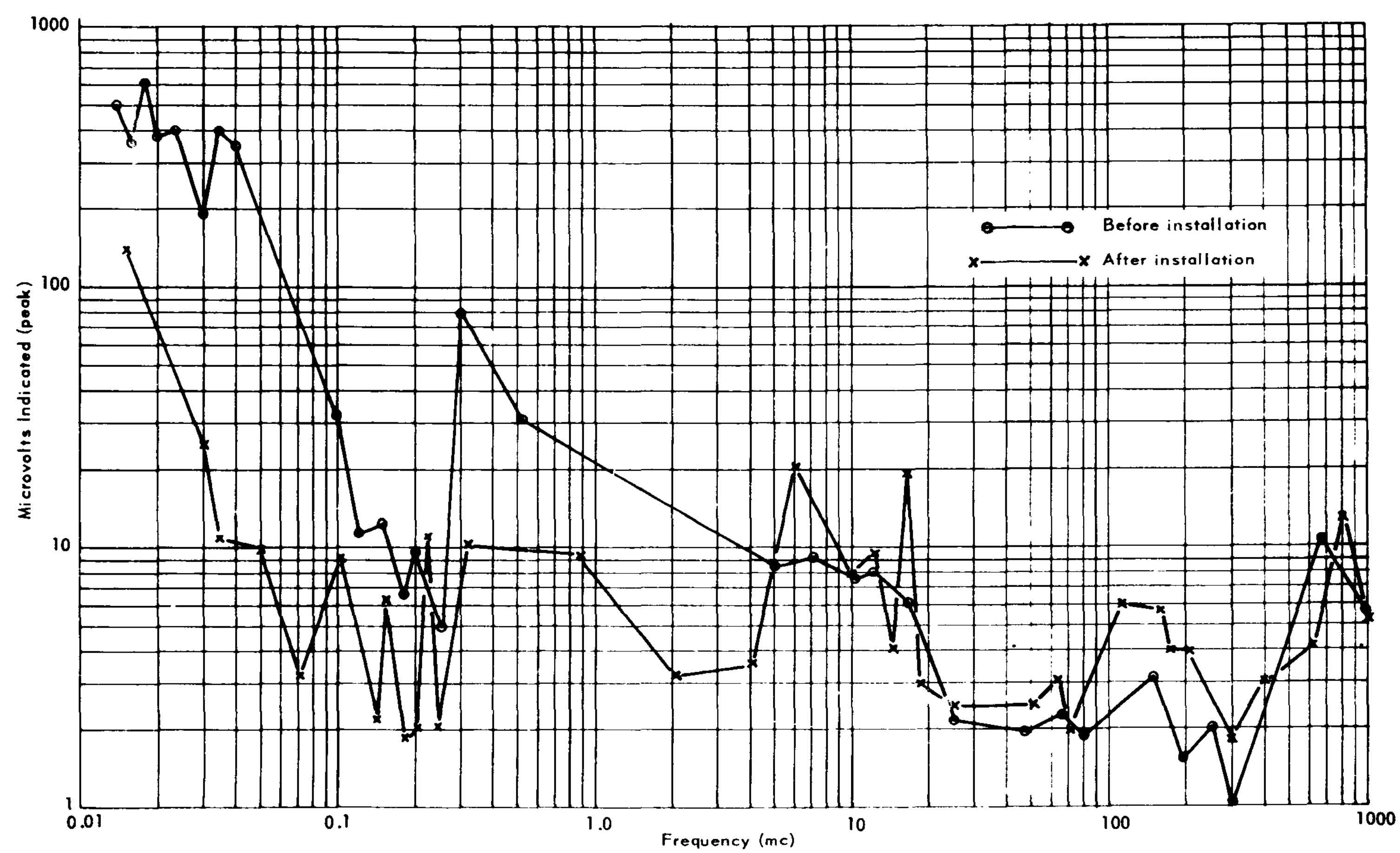

Figure 6. Ambient noise remote from power line, before and after installing lossy line.

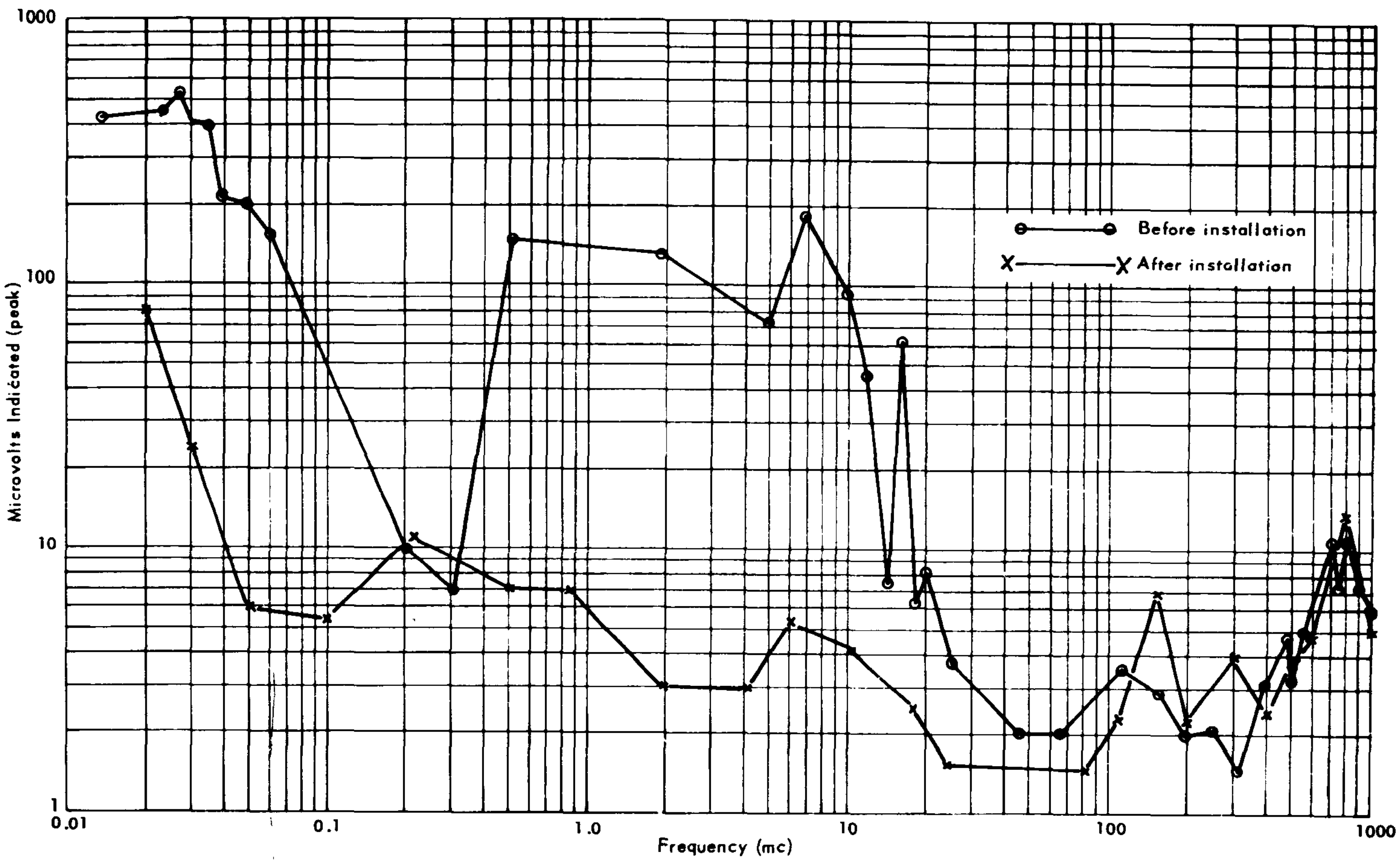

Figure 7. Radiated line noise, 100 feet beyond 1750-foot feeder, before and after installing lossy line.

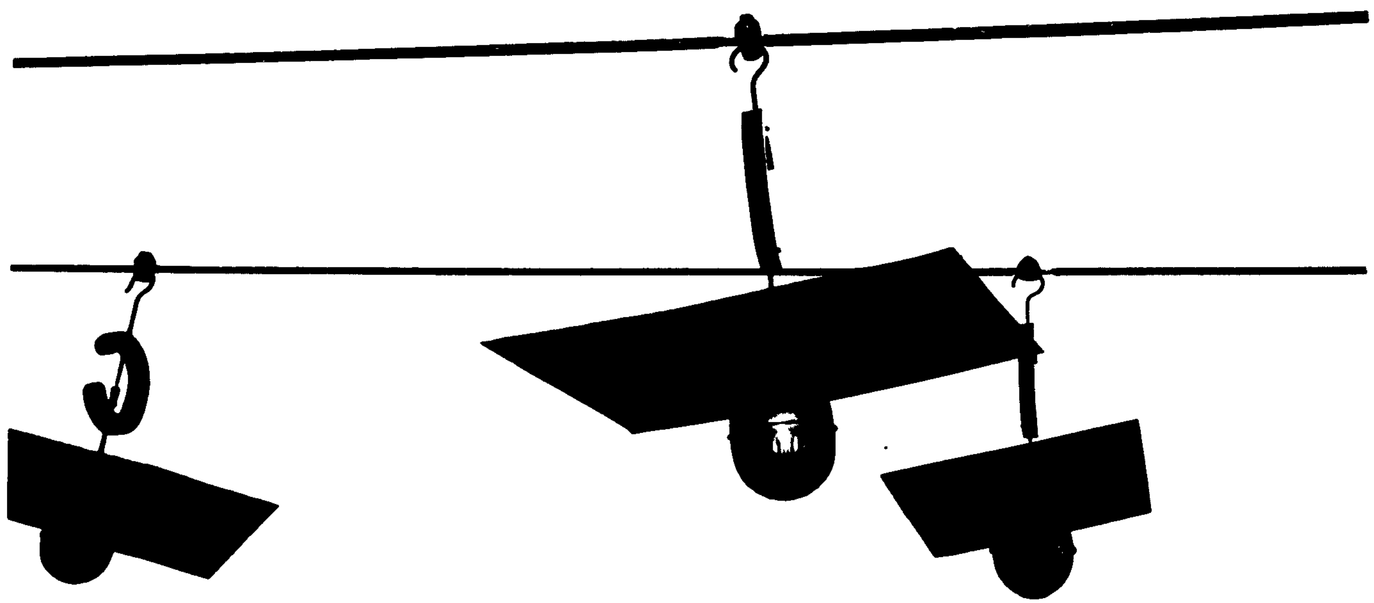

Figure 8. Impulse noise gap generators installed on hot line.

Figure 9. Suppressed 60-cycle generators.

Figure 10. Test set-up.

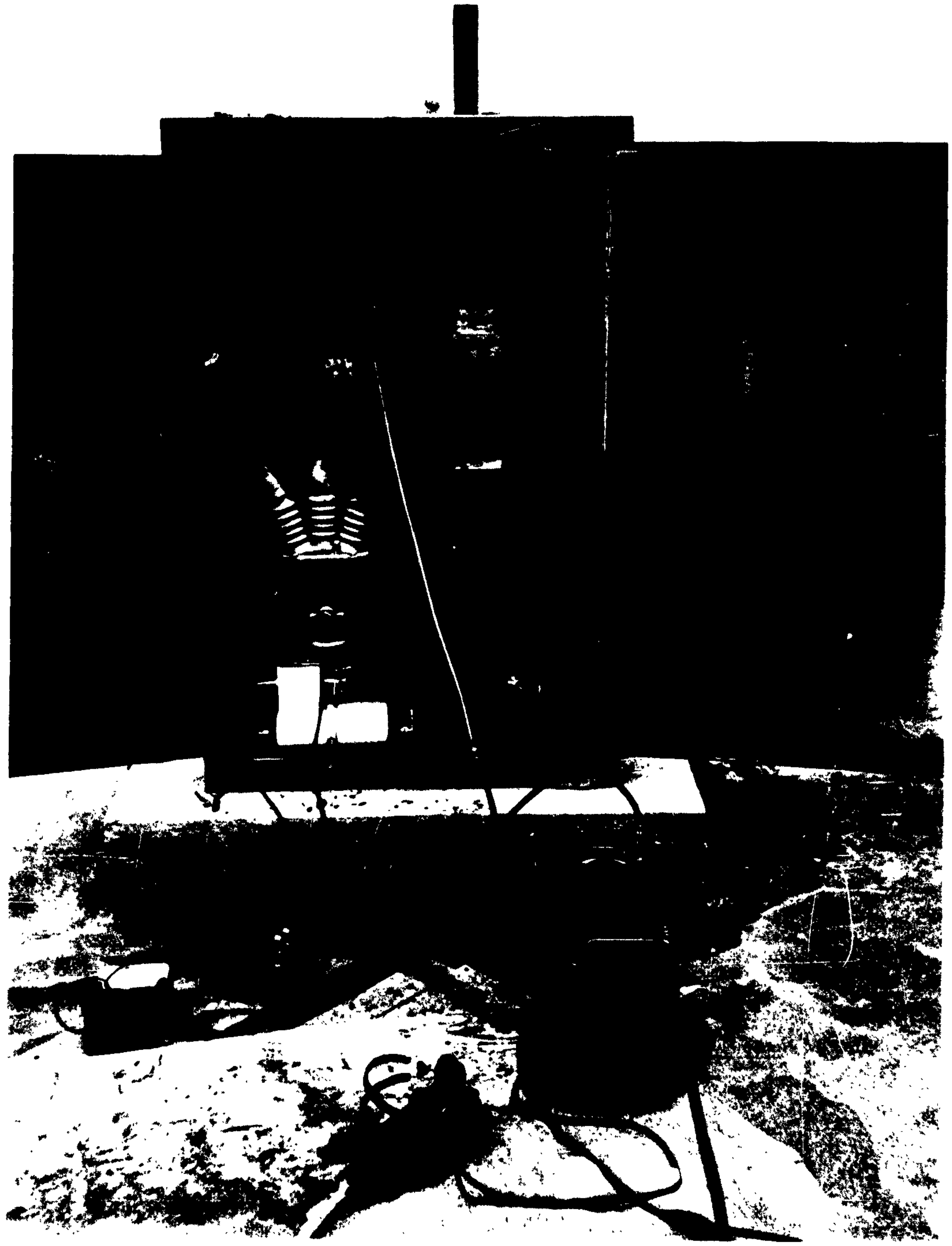

Figure 11. Impulse noise power generator.

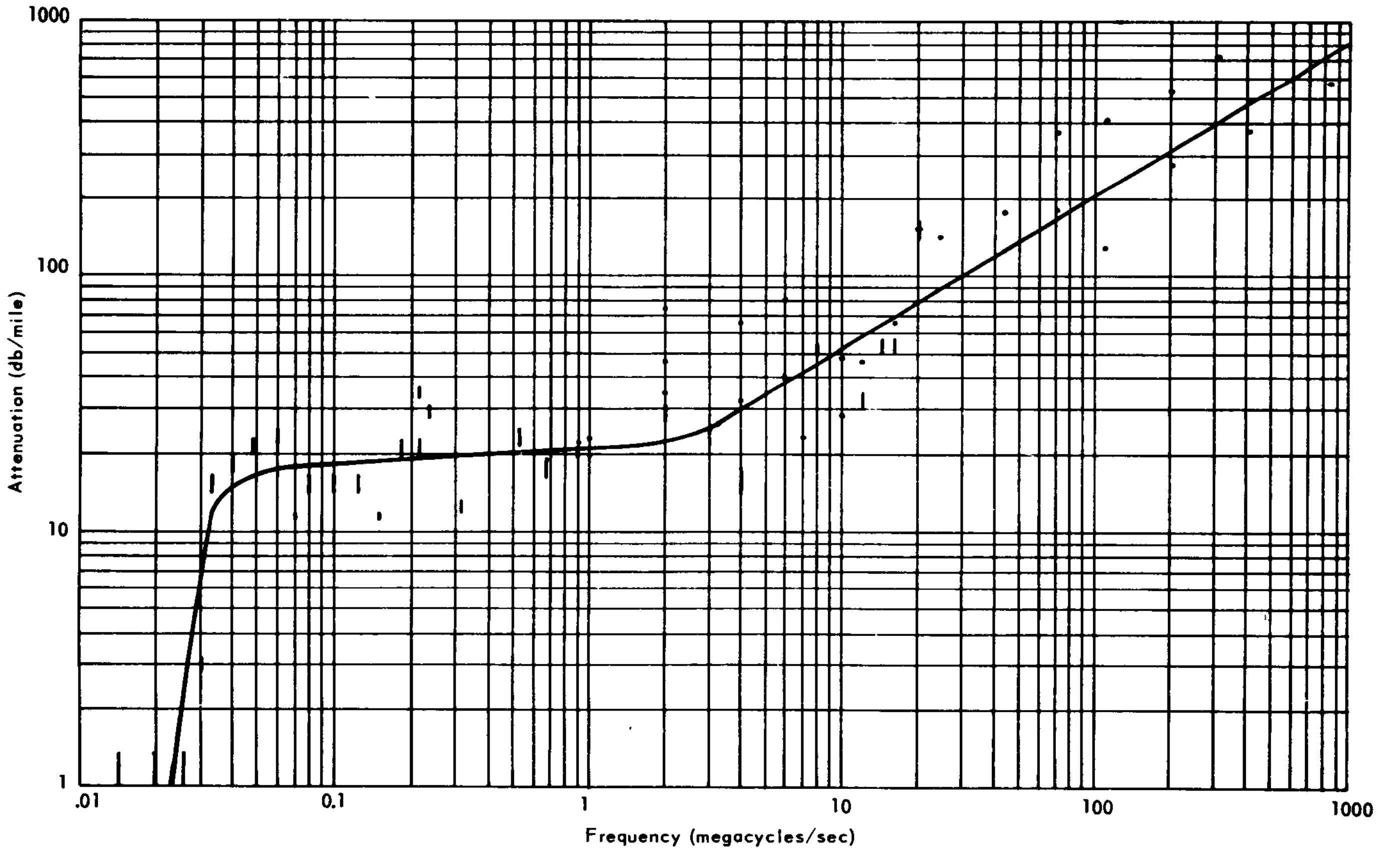

Figure 12. Attenuation curve for lossy line on San Nicolas.

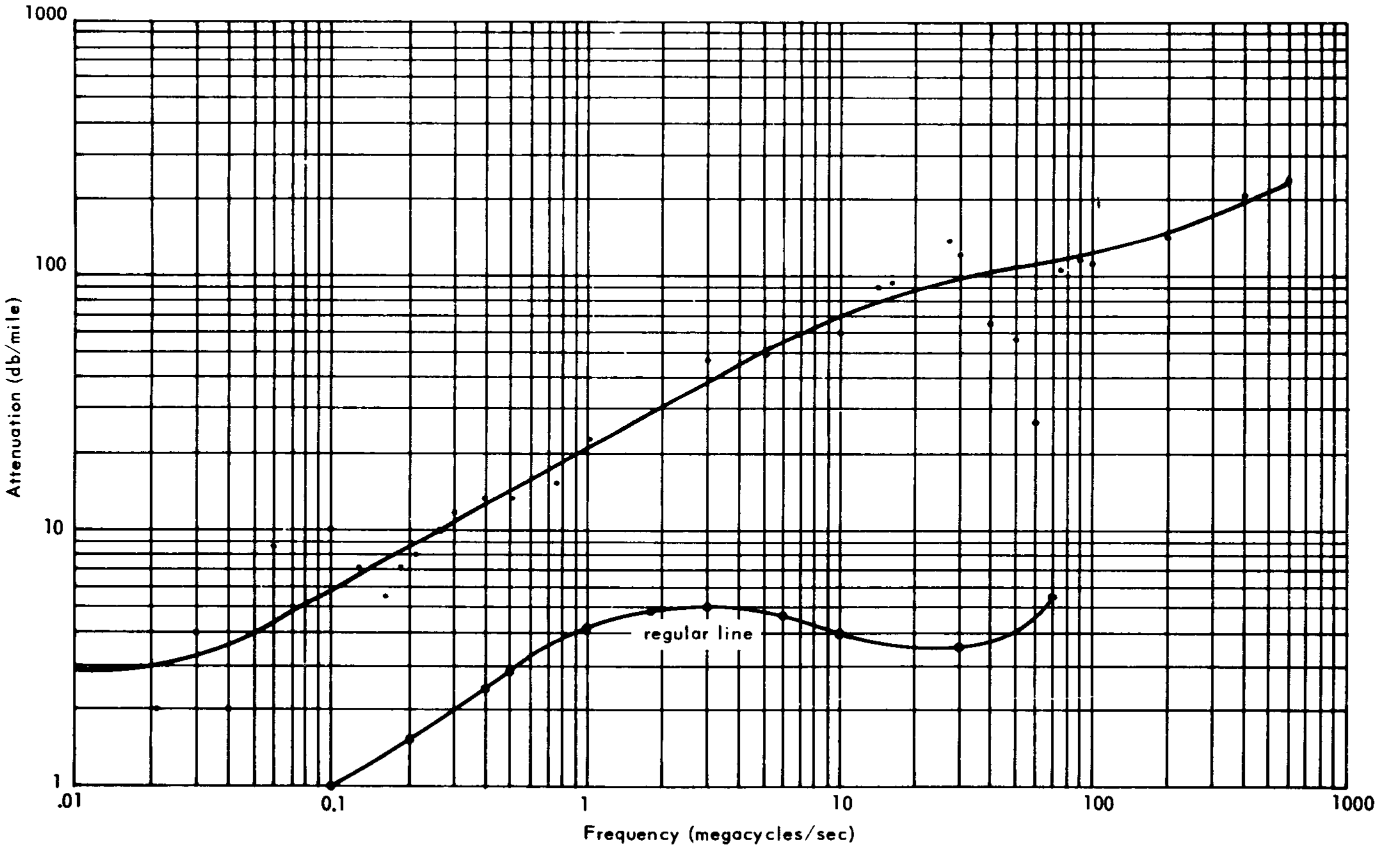

Figure 13. Attenuation curve for lossy line at Fort Huachuca.

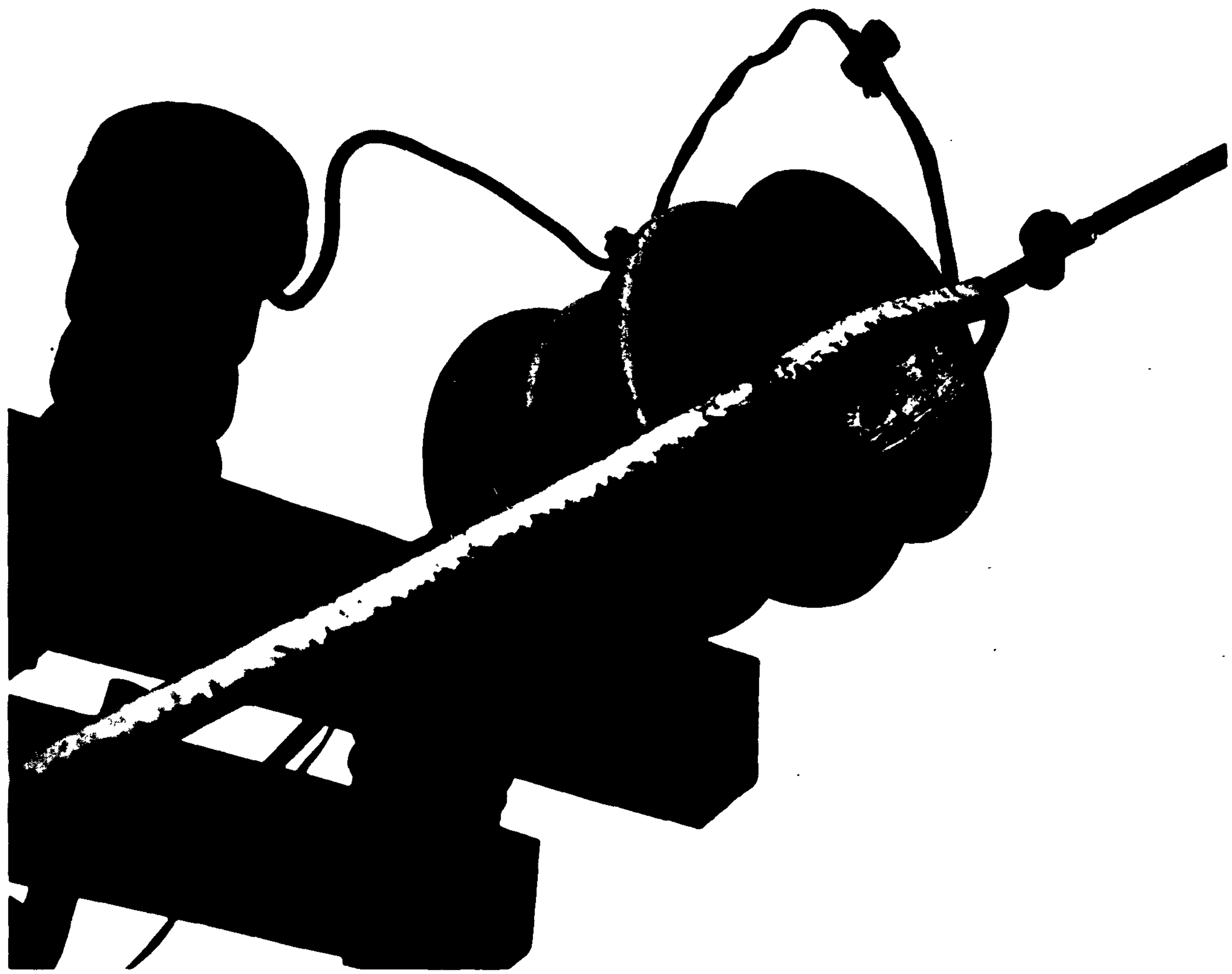

Figure 14. Weather effects on lossy line after two months on San Nicolas.

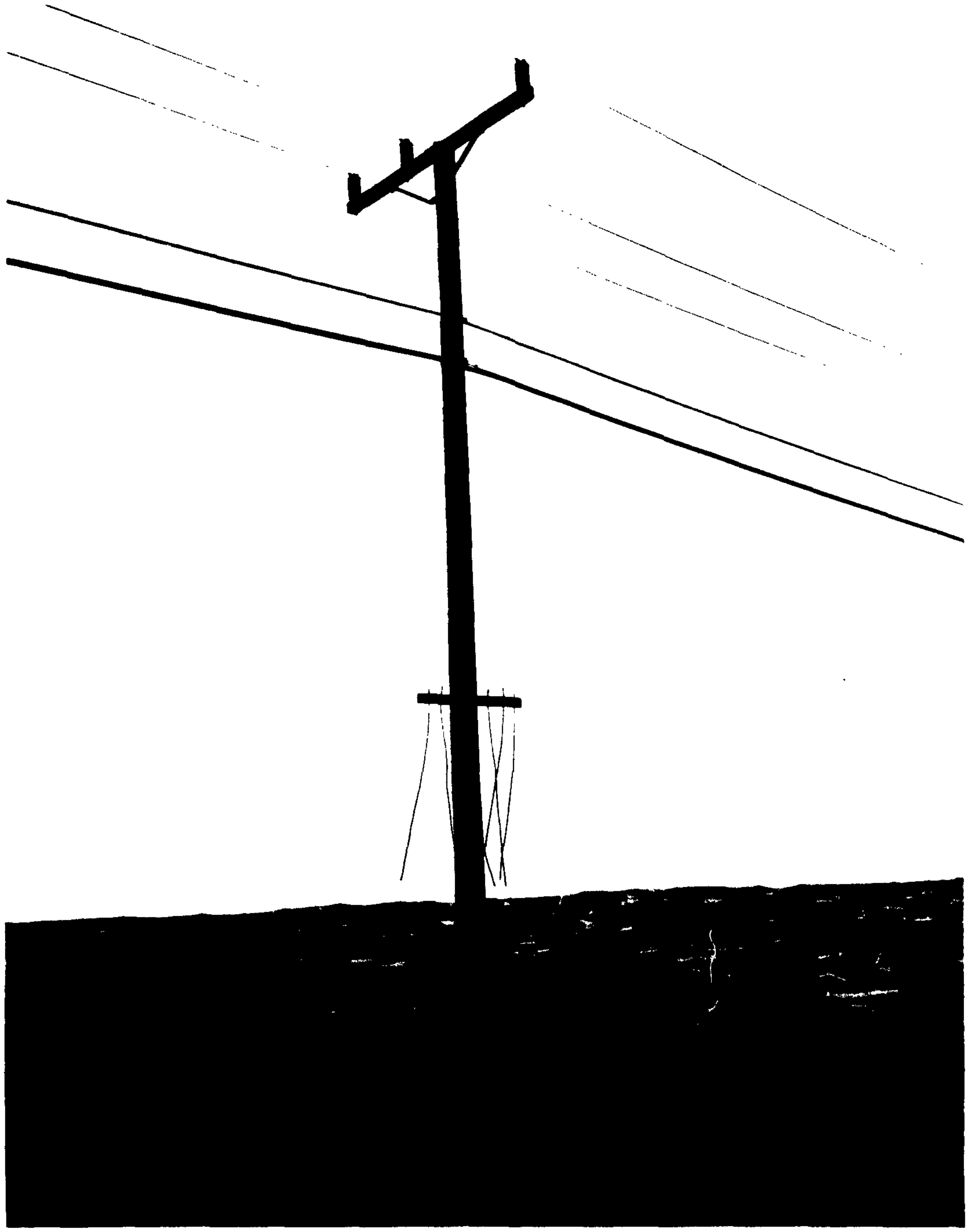

Figure 15. Weathering samples of lossy line on San Nicolas.

Appendix

ELECTROMAGNETIC WAVE PROPAGATION ON LINE WITH REFLECTIONS

The equation for the propagation of an electromagnetic wave on a transmission line with reflections is expressed as:

$$E_x = \frac{E_g Z_o \left(e^{-\gamma x} + K_r e^{-2\gamma \ell} e^{\gamma x}\right)}{(Z_o + Z_g)(1 - K_r K_g e^{-2\gamma \ell})} \qquad (1)$$

where $Z_o = \dfrac{\sqrt{R + j\omega L}}{\sqrt{G + j\omega C}}$

$$\gamma = \alpha + jB = \sqrt{(R + j\omega L)(G + j\omega C)}$$

$$K_g = \frac{Z_g - Z_o}{Z_g + Z_o}$$

$$K_r = \frac{Z_r - Z_o}{Z_r + Z_o}$$

and where B = phase coefficient, propagation wave

C = capacitance per unit length

E_g = generator voltage

E_x = instantaneous voltage at point x

f = frequency in cycles per second

G = conductance per unit length

$j = \sqrt{-1}$

K_g = reflection coefficient, sending end

K_r = reflection coefficient, receiving end

ℓ = total line length = 1 mile

L = inductance per unit length

R = resistance per unit length

x = instantaneous distance down line

Z_g = impedance of buried line sending end or generator

Z_o = characteristic impedance

Z_r = impedance of load at end of line (open)

α = attenuation coefficient, propagation wave

γ = propagation constant

$\omega = 2\pi f$ = angular frequency in radians per second

By rearranging Equation 1,

$$\frac{(Z_o + Z_g)(1 - K_r K_g e^{-2\gamma\ell})}{E_g Z_o} = \frac{e^{-\gamma x} + K_r e^{-2\gamma\ell} e^{\gamma x}}{E_x}$$

Then, by subtracting two expressions for E_{x_1} and E_{x_2},

$$\frac{e^{-\gamma x_1} + K_r e^{-2\gamma \ell} e^{\gamma x_1}}{E_{x_1}} - \frac{e^{-\gamma x_2} + K_r e^{-2\gamma \ell} e^{\gamma x_2}}{E_{x_2}} = 0 \qquad (2)$$

These equations were programmed for the IBM 1620 computer after simplifying by substitutions of the form

$$e^{\gamma x} = e^{(\alpha + jB)x} = e^{\alpha x} (\cos Bx + j \sin Bx)$$

The necessity for determining reflection and impedance constants was eliminated by solving simultaneously the equation of propagation at pairs of points along the line at one frequency, and taking the difference, adjusting both α and B for a minimum sum of differences, and a minimum sum of the square of the differences, as follows: Adjust values of α, B for:

$$\sum_{I=1}^{5} \left(\frac{f(x_I)}{E_I} - \frac{f(x_i)}{E_i} \right) = 0; I \neq i$$

Also for

$$\sum_{I=1}^{5} \left(\frac{f(x_I)}{E_I} - \frac{f(x_i)}{E_i} \right)^2 = 0; I \neq i$$

Values of B for the phase coefficient were varied separately from ranges of values for α, the attenuation coefficient. Fortunately, a first set of guesses for B and α were close to the final fit, and the differences varied slowly with B. The chosen range of values for α resulted in a change of sign in passing from small positive values to negative values for the difference sums. The closeness of fit is shown in Figure 12 by the length of vertical line representing the fit of values of α for all sets of measurement data at each frequency point where the computer was used.

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